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Properties of Building Materials

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ABSTRACT

Thermal and mechanical properties at elevated temperatures are given for various building materials. The thermal properties include thermal conductivity, specific heat, thermal expansion and density. The mechanical properties include strength and modulus of elasticity of the materials. Creep is also discussed. The various materials considered are lightweight and normal weight concrete, steel, claybrick, wood and gypsum.

RÉSUMÉ

L'auteur décrit les caractéristiques thermiques et mécaniques de divers matériaux de construction aux températures élevées. Les caractéristiques thermiques examinées sont les suivantes : conductivité thermique, chaleur spécifique, dilatation thermique et masse volumique. Les caractéristiques mécaniques étudiées sont la résistance et le module d'élasticité. On traite aussi du fluage. Les divers matériaux examinés sont les bétons léger et de poids normal, l'acier, la brique d'argile, le bois et le plâtre.

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PROPERTIES OF BUILDING MATERIALS

Tibor Z. Harmathy

Homogeneous materials, i.e., materials that have the same composition and properties in all their volume elements, are rarely found in nature. Most construction materials are *heterogeneous*, yet their heterogeneity is often glossed over when dealing with practical firesafety problems.

The heterogeneity of concrete is easily noticeable. Other heterogeneities related to the microstructure of materials, i.e., their *grain* and *pore structures*, are not detectable by the naked eye. The microstructure depends greatly on the way the materials are formed. In general, those materials formed by solidification from a melt show the highest degree of homogeneity. The result of the solidification is normally a *polycrystalline* material, which comprises polygonal *grains* of crystals of random orientations. Severe *cold-working* in metals may produce an elongated grain structure and crystals with preferred orientations.

If cooled rapidly, some nonmetallic materials may assume an *amorphous* or glassy structure. Glassy materials have a liquidlike, grainless microstructure with low crystalline order. On heating they will go through a series of phases of decreasing viscosity.

Synthetic polymers are made up of very large molecules. In the case of *thermoplastics*, on heating the molecular chains become more mobile relative to one another. The material softens, much like glass. In *thermoset* materials, cross-bonds between the molecular chains prevent the loosening of the molecular structure and any change into a liquidlike state.

Some building materials are formed from a wet, plastic mass or from compacted powders by firing. The resulting product is a polycrystalline solid with a well-developed pore structure.

Two important building materials, concrete and gypsum, are formed by mixing finely ground powders (and aggregates) with water. The mixture solidifies by hydration. The cement paste in a concrete has a highly complex microstructure that is interspersed with very fine, elaborate pores.

Most building materials can be treated as *isotropic* materials, i.e., as though they possessed the same properties in all directions. Among their properties, those that are well-defined by the composition and phase are *structure-insensitive*. Some others depend on the microstructure of the solid or on its previous history. These properties are *structure-sensitive*.

POROSITY AND MOISTURE SORPTION

What is commonly referred to as a solid is actually all the material within the visible boundaries of a solid object. Clearly, if the solid is porous—and most building materials are—the so-called solid consists of at least two phases: a solid-phase matrix, and a gaseous phase (namely, air), in the pores within the matrix. Usually, however, there is also a liquid or liquidlike phase present: moisture either adsorbed from the atmosphere to the pore surfaces, or held in the pores by capillary condensation. This third phase is always present if the pore structure is *continuous*; *discontinuous* pores (like the pores of some foamed plastics) are not readily accessible to atmospheric moisture.

The pore structure of materials is characterized by two properties: *porosity*, P (m^3/m^3), which is the volume fraction of pores within the visible boundaries of the solid; and *specific surface*, S (m^2/m^3), the surface area of the pores per unit volume of the material. For a solid with continuous pore structure, the porosity is a measure of the maximum amount of water the solid can hold when saturated. The specific surface and (to a lesser degree) porosity together determine the moisture content the solid can hold in equilibrium with given atmospheric conditions.[1]

The *sorption isotherm* shows the relationship at constant temperature between the equilibrium moisture content of a porous material and relative atmospheric humidity. A sorption isotherm usually has two branches: an *adsorption branch*, obtained by monotonically increasing the relative humidity of the atmosphere from 0 to 100 percent through very small equilibrium steps; and the *desorption branch*, obtained by monotonically lowering the relative humidity from 100 to 0 percent. Derived experimentally, the sorption

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isotherms offer some insight into the nature of the material's pore structure.[1]

For heterogeneous materials consisting of solids of different sorption characteristics (e.g., concrete, consisting of cement paste and aggregates), the sorption isotherms can be estimated[1] using the simple mixture rule (with $\zeta = 1$; see Equation 1).

Among the common building materials, only concrete (or more accurately, the cement paste in the concrete) and wood, because of their large specific surfaces, can hold water in amounts substantial enough to be taken into consideration in fire performance assessments.

MIXTURE RULES

Some properties of materials of mixed composition or mixed phase can be calculated by simple rules if the material properties for the constituents are known. The simplest mixture rule[2] is

$$\pi = \sum_i v_i \pi_i \tag{1}$$

where π is a material property for the composite, π_i is that for the composite's ith constituent, v_i (m^3/m^3) is the volume fraction of the ith constituent in the composite, and ζ has a value between -1 and $+1$.

Hamilton and Cosser[3] recommended the following rather versatile formula for two-phase solids

$$\pi = \frac{v_1\pi_1 + xv_2\pi_2}{v_1 + xv_2} \tag{2}$$

where

$$x = \frac{n\pi_1}{(n-1)\pi_1 + \pi_2} \tag{3}$$

Here, phase 1 must always be the principal continuous phase, n is a function of the phase distribution geometry and, in general, has to be determined experimentally. With $n \to \infty$ and $n = 1$, Equation 2 converts to Equation 1 with $\zeta = 1$ and $\zeta = -1$, respectively. With $n = 3$, a relation is obtained for a two-phase system where the discontinuous phase consists of spherical inclusions.[4]

By repeated application, Equations 2 and 3 can be extended to a three-phase system,[5] e.g., to a moist, porous solid, which consists of three essentially continuous phases (the solid matrix, with moisture and air in its pores).

SURVEY OF BUILDING MATERIALS

There are *combustible* and *noncombustible* building materials. To a designer concerned with the structural performance of a building during a fire, the mechanical and thermal properties of these materials are of principal interest. Yet, combustible building materials may become ignited, and thereby the positive role assigned to them by design (i.e., functioning as structural elements of the building), may change into a negative role: becoming fuel and adding to the severity of fire. Information on those properties of combustible building materials that are related to the latter role is woefully inadequate and will, in all likelihood, remain outside the scope of any comprehensive handbook on fire science for some time to come.

From the point of view of the role materials play in the structural performance of buildings in fire, materials can be grouped as follows:

1. Group L (load-bearing materials): materials designed to carry high stresses, usually in tension. Clearly, for group L materials, the mechanical properties related to their behavior in tension are of principal interest to the designer.
2. Group L/I (load-bearing/insulating materials): materials designed to carry moderate stresses and, in fire, to provide insulation to group L materials. For group L/I materials, both the mechanical properties (related mainly to behavior in compression) and the thermal properties are of interest.
3. Group I (insulating materials): materials not designed to carry load. Their role in fire is to resist heat transmission through building elements and/or to provide insulation to group L materials. For group I materials, only the thermal properties are of interest.

The number of building materials has been increasing dramatically during the past few decades. By necessity, only a few of those commonly used will be discussed in this chapter in some detail. These materials are: in group L, structural steel and prestressing steel; in group L/I, concrete, brick, and wood; and in group I, gypsum.

BUILDING MATERIALS AT ELEVATED TEMPERATURES

While calculation techniques for predicting the process of deterioration of constructions in fire have become highly sophisticated in recent years, research related to supplying input information into these calculations has not kept pace. The designer of the firesafety features of buildings will find that information on the properties of building materials for the temperature range of interest, 20 to 700°C, is difficult to uncover. Most building materials are not stable throughout this temperature range. On heating they undergo physicochemical changes, accompanied by transformations in their microstructure, and, at the same time, changes in their properties. A concrete at 500°C is completely different from the same material at room temperature.

Clearly, the generic information available on the properties of building materials at room temperature is seldom applicable in firesafety design. Progress in materials science will mark true progress in fire science during the next few decades.

REFERENCE CONDITION

Most building materials are porous and therefore capable of holding a certain amount of moisture, depending on atmospheric conditions. Since the presence of moisture may have a significant and often unpredictable effect on the properties of materials at any temperature below 100°C, it is imperative to conduct all property tests on specimens brought into a moistureless "reference condition" by some drying technique prior to the test. The reference condition is normally interpreted as that attained by heating the test specimen in an oven at 105°C until its weight shows no change. A few building materials, however, among them all gypsum products, may undergo irreversible physicochemical changes when held at that temperature for an extended period. To bring them to a reference condition, specimens of

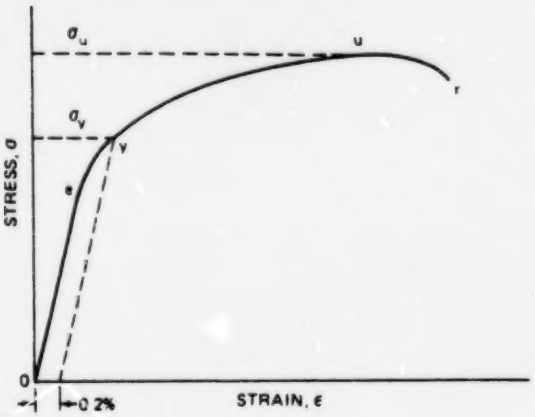


Fig. 1-26.1. Stress-strain curve (strain rate is roughly constant).

these materials should be heated in a vacuum oven at some lower temperature level (e.g., at 40°C in the case of gypsum products).

MECHANICAL PROPERTIES

Stress-Strain Curve

The mechanical properties of solids are usually derived from conventional tensile or compressive tests. Figure 1-26.1, shows the variation of stress, σ (MPa), with increasing deformation (or strain), ε (m/m), while the material is deformed (strained) at a more or less constant rate (i.e., constant crosshead speed), usually of the order of 1 mm/min.

Modulus of Elasticity, Yield Strength, Ultimate Strength

Section 0-*e* of the curve in Figure 1-26.1 represents the elastic deformation of the material, which is instantaneous and reversible. The modulus of elasticity, E (MPa), is the slope of that section. Between points *e* and *u* the deformation is plastic, nonrecoverable, and quasi-instantaneous. The plastic behavior of the material is characterized by the yield strength at 0.2 percent offset, σ_y (MPa), and the ultimate strength, σ_u (MPa). After some localized necking (reduction of cross-sectional area), the material ruptures at point *r*. The modulus of elasticity is more or less a structure-insensitive property.

For steels of similar metallurgical characteristics, the stress-strain curve can be reproduced at room temperature at a reasonable tolerance and the shape of the curve does not depend on the crosshead speed (within limits). At elevated temperature, the material undergoes plastic deformation even at constant stress, and the *e-r* section of the stress-strain curve depends markedly on the crosshead speed.

Creep

The time-dependent plastic deformation of the material is referred to as creep strain, and is denoted by ε_t (m/m). In a creep test the variation of ε_t is recorded against time, t (h), at constant stress (more accurately, at constant load) and at constant temperature, T (K). A typical strain-time curve is shown in part a of Figure 1-26.2. The total strain is

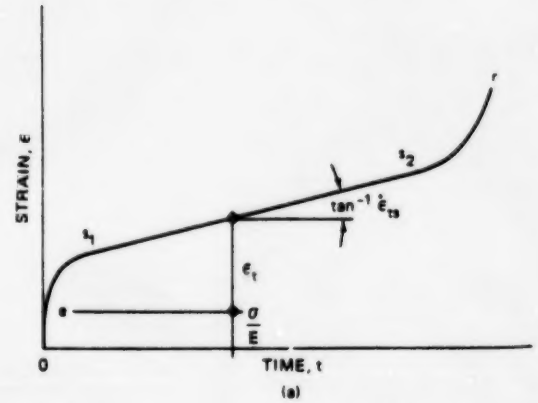
$$\varepsilon = \frac{\sigma}{E} + \varepsilon_t \tag{4}$$

The 0-*e* section of the stress-time curve represents the instantaneous elastic (and recoverable) part of the curve; the rest is creep, which is essentially nonrecoverable. The creep is fast at first (primary creep, section *e*-s_1 in Figure 1-26.2), then proceeds for a long time at an approximately constant rate (secondary creep, section s_1-s_2), and finally accelerates until rupture occurs (tertiary creep, section s_2-*r*). The curve becomes steeper if the test is conducted either at a higher load (stress) or at a higher temperature.

Dorn's creep concept[6] is particularly suitable for dealing with deformation processes developing at varying temperatures. Dorn eliminated the temperature as a separate variable by combining it with time

$$\theta = \int_0^t e^{-\Delta H/RT}\, dt \tag{5}$$

where θ is temperature-compensated time (h), ΔH is the activation energy of creep [J/(kmol)], and R is the gas constant [J/(kmol)K].



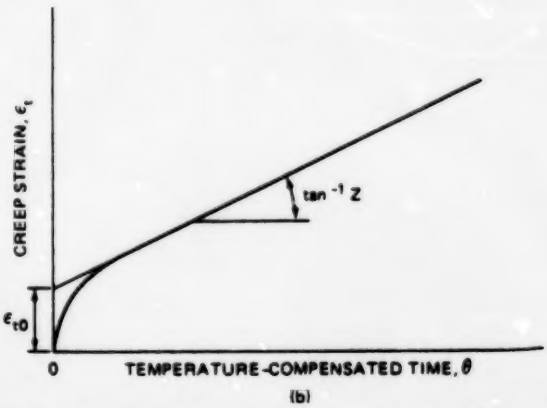


Fig. 1-26.2. (a) Strain-time curve; T = constant, σ = constant (b) creep strain versus temperature-compensated time curve σ = constant.

From a practical point of view, only the primary and secondary creep are of importance. It has been shown[7,8] that the creep strain in these two regimes can be satisfactorily described by the following equation

$$\varepsilon_t = \frac{\varepsilon_{t0}}{\ln 2} \cosh^{-1}(2^{Z\theta + \varepsilon_{t0}}) \tag{6}$$

or approximated by the simple formula

$$\varepsilon_t \approx \varepsilon_{t0} + Z\theta \tag{7}$$

where Z is the Zener-Hollomon parameter (h^{-1}), and ε_{t0} is another creep parameter (m/m), the meaning of which is explained in part (b) of Figure 1-26.2. The Zener-Hollomon parameter is defined as[9]

$$Z = \dot{\varepsilon}_{ts} e^{\Delta H/RT} \tag{8}$$

where $\dot{\varepsilon}_{ts}$ is the rate of secondary creep (h^{-1}), at temperature, T. The two creep parameters, Z and ε_{t0}, are functions of the applied stress only (i.e., independent of the temperature).

For most materials creep becomes noticeable only if the temperature is higher than about one-third of the melting temperature. The creep of concrete at room temperature is due to the presence of water in its microstructure.[10] Mukaddam and Bresler[11] and Schneider[12] described procedures for correlating experimental creep data for concrete at moderately elevated and high temperatures, respectively.

THERMAL PROPERTIES

Dilatometric Curves

The dilatometric curve is a record of the fractional change of a linear dimension of a solid at steadily increasing or decreasing temperature. With mathematical symbolism, the dilatometric curve is a plot of

$$\frac{\Delta \ell}{\ell_0} \quad \text{against} \quad T$$

where $\Delta \ell = \ell - \ell_0$, and ℓ and ℓ_0 are the changed and original dimensions of the solid (m), respectively, the latter usually taken at room temperature. $\Delta \ell$ reflects not only the linear expansion or shrinkage of the material, but also the dimensional effects brought on by possible physicochemical changes ("reactions," in a generalized sense).

The heating of the solid usually takes place at an agreed-upon rate, 5°C/min as a rule. Because the physicochemical changes proceed at a finite rate and some of them are irreversible, the dilatometric curves obtained by heating the material rarely coincide with those obtained during the cooling cycle. Sluggish reactions may bring about a steady rise or decline in the slope of the dilatometric curve; fast reactions may appear as discontinuities in the slope. Heating the material at a rate higher than 5°C/min usually causes the reactions to shift to higher temperatures and to develop faster.

Most of the dilatometric curves to be shown were recorded and reported earlier.[13] A horizontal dilatometric apparatus was used, made to the design of the British Ceramic Research Association by a British manufacturer and modified to make it suitable for automatic operation.[14] The sample was 76.2 mm long and about 13 by 13 mm in cross section. It was subjected to a small spring load which varied during the test. Unfortunately, even this small load caused creep shrinkage with those materials that tended to soften at higher temperatures. Furthermore, since the apparatus did not provide a means for placing the sample in a nitrogen atmosphere, in certain cases oxidation may also have had some effect on the shape of the curves.

Thermogravimetric Curves

The thermogravimetric curve is a record of the fractional variation of the mass of a solid at steadily increasing or decreasing temperature. Again, with mathematical symbolism, a thermogravimetric curve is a plot of

$$\frac{M}{M_0} \quad \text{against} \quad T$$

where M and M_0 are the changed and original masses of the solid (kg), respectively, the latter usually taken at room temperature. If the curve is obtained by heating the solid, the agreed-upon rate of heating is, again, 5°C/min.

The thermogravimetric curves reflect reactions accompanied by loss or gain of mass but, naturally, do not reflect changes in the materials' microstructure or crystalline order. $M/M_0 = 1$ is the thermogravimetric curve for a chemically inert material. Again, an increase in the rate of heating usually causes the chemical reactions to shift to higher temperatures and to develop faster.

The thermogravimetric curves to be shown were obtained by a DuPont 951 thermogravimetric analyzer,[15] using specimens of 10 to 30 mg in mass, placed in a nitrogen atmosphere. The rate of temperature rise was 5°C/min.[13]

Density, Porosity

The density, ρ (kg/m^3), in oven-dry condition, is the mass of a unit volume of the material, comprising the solid itself and the gas-filled pores. Assuming that the material is isotropic with respect to its dilatometric behavior, its density at any temperature can be calculated from the thermogravimetric and dilatometric curves.

$$\rho = \rho_0 \frac{\left(\frac{M}{M_0}\right)_T}{\left[1 + \left(\frac{\Delta \ell}{\ell_0}\right)_T\right]^3} \tag{9}$$

where ρ_0 is the density of the solid at the reference temperature (usually room temperature), and the T subscript indicates values pertaining to temperature T in the thermogravimetric and dilatometric records.

The mixture rule in its simplest form (Equation 1 with $\zeta = 1$) applies to the density of composite solids.

$$\rho = \sum_i v_i \rho_i \tag{10}$$

where the i subscript relates to information on the ith component. If, as usual, the composition is given in mass fractions rather than volume fractions, the volume fractions are to be calculated as

$$v_i = \frac{\frac{w_i}{\rho_i}}{\sum_i \frac{w_i}{\rho_i}} \tag{11}$$

where w_i is the mass fraction of the ith component (kg/kg).

True density, ρ, (kg/m^3), is the density of the solid in a poreless condition. Many building materials are nonexistent in such condition, and therefore ρ, may be a theoretical value derived on crystallographic considerations, or determined by some standard technique, e.g., ASTM C-135.[16] The relationship between the porosity and density is

$$P = \frac{\rho_t - \rho}{\rho_t} \tag{12}$$

The overall porosity of a composite material consisting of porous components is

$$P = \sum_i v_i P_i \tag{13}$$

where again the i subscript relates to the ith component of the material.

Calorimetric Curves

A calorimetric curve describes the variation with temperature of the apparent specific heat of a material at constant pressure, c_p (J/kg K). The apparent specific heat is defined as

$$c_p = \left(\frac{\partial h}{\partial T}\right)_p \tag{14}$$

where h is enthalpy (J/kg), and the p subscripts indicate the constancy of pressure. If the heating of the solid is accompanied by physicochemical changes ("reactions"), the enthalpy becomes a function of the degree of conversion from the reactant(s) into the product(s), ξ (dimensionless). For any temperature range where conversion takes place,[5,17] i.e., for $0 \le \xi \le 1$

$$c_p = \bar{c}_p + \Delta H_p \frac{d\xi}{dT} \tag{15}$$

where $\bar{c}_p$ is the specific heat for that mixture of reactants and (solid) products that the material consists of at a given stage of the conversion, characterized by ξ, and ΔH_p is the latent heat associated with the conversion (J/kg).

As this equation and Figure 1-26.3 show, in temperature intervals of physicochemical instability the apparent specific heat consists of sensible heat and latent heat contributions. The latter contribution will result in a peak in the calorimetric curve; a maximum if the reaction is endothermic, minimum if it is exothermic.

In heat flow studies it is usually the ρc_p product rather than c_p that is needed as input information. This product is referred to as "volumetric" specific heat.

For a long time adiabatic calorimetry was the principal method to study the shape of the c_p versus T relationship. Today, differential scanning calorimetry (DSC) is the most commonly used technique for mapping the curve in a single temperature sweep at a desired rate of heating. Unfortunately, the accuracy of the DSC technique in determining the sensible heat contribution to the apparent specific heat may not be particularly good (sometimes it may be as low as ±20 percent).

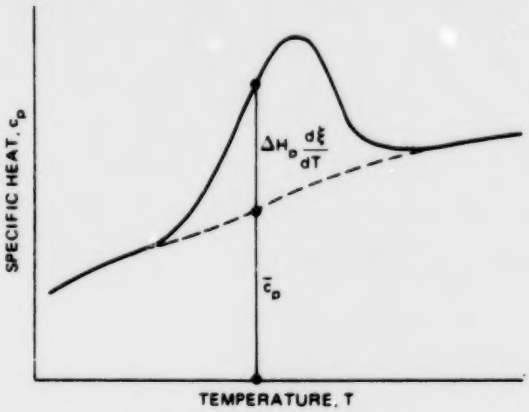


Fig. 1-26.3. The apparent specific heat.

The rate of heating is, again, usually 5°C/min. At higher heating rates the peaks in the DSC curves tend to shift to higher temperatures and become sharper.

Materials that undergo exothermic reactions may yield negative values in the calorimetric curve. A negative value for c_p indicates that at the applied (and enforced) rate of heating, the rate of evolution of reaction heat exceeds the rate of absorption of sensible heat by the material. In natural processes the apparent specific heat can never be negative, because the heat evolving from the reaction is either scattered to the surroundings, or if absorbed by the material, causes a very fast temperature rise. If the heat of reaction is not very high, obtaining nonnegative values for c_p can be achieved by suitably raising the scanning rate. For this reason, some materials undergoing exothermic reactions must be tested at rates of heating higher than 5°C/min, often as high as 50°C/min.

Some of the information in this section was developed with the aid of a DuPont 910 differential scanning calorimeter.[13,18] The samples were of a mass of 10 to 30 mg and were placed in a nitrogen atmosphere. The rate of temperature rise was usually 5°C/min.

If experimental information is not available, the c_p versus T relation can be calculated from data on heat capacity and heat of formation, tabulated in a number of handbooks.[19,20] The specific heat of compounds not listed in handbooks can often be estimated with the aid of the Neumann-Kopp law concerning the additivity of heat capacities. Examples of such calculations can be found in Ref. 5 where, based on handbook data, information is developed for the apparent specific heat versus temperature relation for three cement pastes and four concretes.

THERMAL CONDUCTIVITY

Heat transmission solely by conduction can occur only in poreless, nontransparent solids. In porous solids (most building materials) the mechanism of heat transmission is a combination of conduction, radiation, and convection. The

thermal conductivity for such solids is, in a strict sense, merely a convenient empirical factor that makes it possible to describe the heat transmission process with the aid of the Fourier law. That empirical factor will depend on the conductivity of the solid matrix as well as on the porosity and pore size of the solid. At higher temperatures, because of the increasing importance of radiant heat transmission through the pores, conductivity becomes sensitive to the temperature gradient.

Measured values of the thermal conductivity depend on the temperature gradient employed in the test, and therefore great discrepancies may be found in thermal conductivity data reported by various laboratories. A thermal conductivity value yielded by a particular technique is, in a strict sense, applicable only to heat flow processes similar to that employed in the technique used.

Experimental data indicate that porosity is not a greatly complicating factor as long as it is not larger than about 0.1. With insulating materials, however, the porosity may be 0.8 or higher. Conduction through the solid matrix may be an insignificant part of the overall heat transmission process; using the Fourier law of heat conduction in analyzing heat transmission may lead to deceptive conclusions.

If the solid is not oven-dry, any temperature gradient in it will create a migration of moisture, mainly by an evaporation-condensation mechanism.[21] The migration of moisture is usually but not necessarily in the direction of heat flow, and manifests itself as an increase (or decrease) in the apparent thermal conductivity of the solid. Furthermore, even oven-dry solids may undergo decomposition (mainly dehydration) reactions at higher temperatures. The sensible heat carried by the gaseous decomposition products as they move in the pores adds to the complexity of the heat flow process. At present there is no way of satisfactorily accounting for these mass transfer processes in studies of heat flow processes occurring under fire conditions.

The thermal conductivity of layered, multiphase solid mixtures depends on whether the phases lie in the direction of, or normal to, the direction of heat flow. The simple mixture rule is applicable, with $\zeta = 1$ in the former case and $\zeta = -1$ in the latter. Thus, in those two limiting cases

$$k = \sum_i v_i k_i \tag{16}$$

and

$$\frac{1}{k} = \sum_i \frac{v_i}{k_i} \tag{17}$$

where k and k_i are the thermal conductivities of the mixture and its constituents (W/m K), respectively.

There is substantial evidence[5,22] that Equations 2 and 3, with $n = 3$, are applicable to any two-phase material consisting of a continuous and a discontinuous solid phase, irrespective of the geometry of the discontinuous phase.

$$k = \frac{v_1 k_1 + \alpha v_2 k_2}{v_1 + \alpha k_2} \tag{18}$$

where

$$\alpha = \frac{3k_1}{2k_1 + k_2} \tag{19}$$

and the subscripts 1 and 2 relate to the continuous and discontinuous phases, respectively. When both phases are essentially continuous, as with most porous materials (with air as the second phase), a lower value of n seems to be applicable:[5] about $n = 1.5$. If the conductivity of air is negligibly small in comparison with that of the solid, the following is a good approximation

$$k = k_s(1 - P) \tag{20}$$

where k_s is the conductivity of the solid itself (W/m K). At higher temperatures, however, the pores become conductive because of radiation. The thermal conductivity is customarily expressed as a sum of two terms

$$k = k_s(1 - P) + k_R \tag{21}$$

where

$$k_R = 4\sigma F d_p T^3 \tag{22}$$

and k_R is the so-called radiant conductivity (W/m K), σ is the Stefan-Boltzmann constant (W/m^2K^4), d_p is the characteristic pore size (m), and F is a constant characteristic of the material and the pore geometry (dimensionless).[23]

The thermal conductivity of solids is a structure-sensitive property. If a solid is crystalline, its conductivity is relatively high at room temperature but gradually decreases as the temperature rises. If, on the other hand, it is predominantly amorphous, its conductivity is low at room temperature and increases slightly with temperature. The conductivity of porous crystalline materials may also increase at very high temperatures because of the radiant conductivity of the pores.

Unfortunately, to the author's knowledge, no scanning technique is available for the acquisition of a continuous thermal conductivity versus temperature curve from a single test. Such a curve must be estimated from the results of tests conducted at various temperature levels. Special problems arise in the temperature intervals of physicochemical insta-

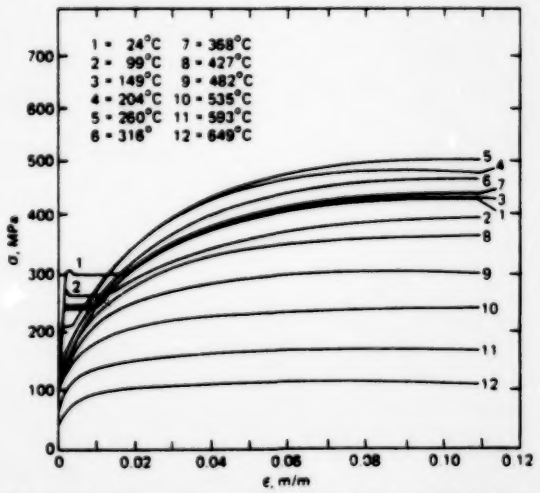


Fig. 1-26.4. Stress-strain curves for structural steels (ASTM A-36) at elevated temperatures.[30]

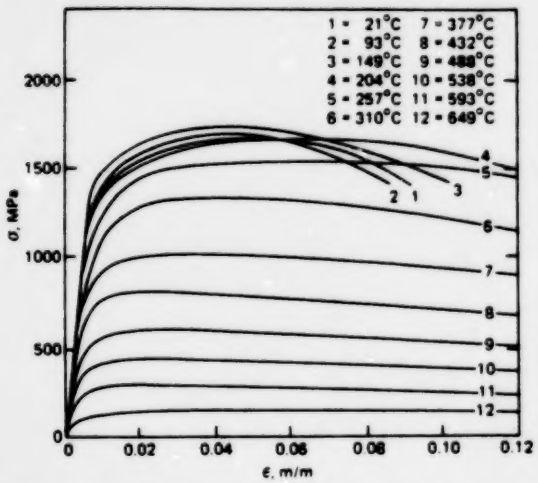


Fig. 1-26.5. Stress-strain curves for prestressing steel (ASTM A-421) at elevated temperatures.[30]

bility. Both the steady-state and variable-state techniques of measuring thermal conductivity require the stabilization of either a temperature level or a temperature distribution, and therefore a certain microstructural condition in the specimen prior to the test. The test results can be viewed as points on a continuous thermal conductivity versus temperature curve obtained by an imaginary scanning technique performed at an extremely slow scanning rate. Since each point pertains to a more or less stabilized microstructural pattern, there is

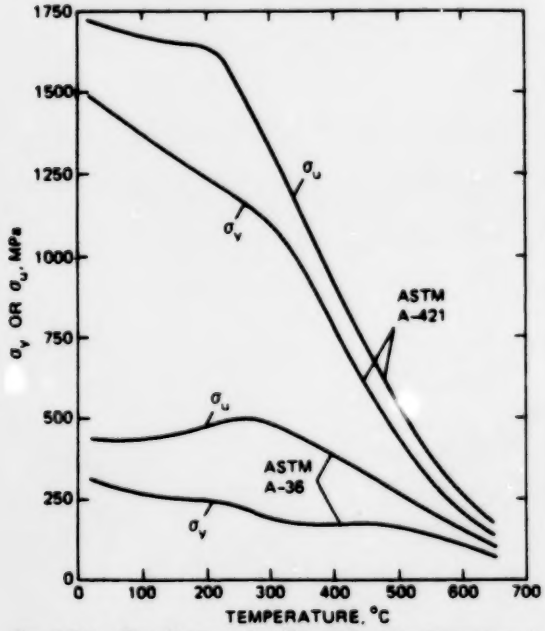


Fig. 1-26.6. The ultimate and yield strengths of a structural steel (ASTM A-36) and a prestressing steel (ASTM A-421).[30]

TABLE 1-26.1. *Creep Properties of Two Typical Steels*

Steel	$\Delta H/R$ (K)	$Z(\sigma)$ (h^{-1})	$\varepsilon_{cr}(\sigma)$ (dimensionless)
ASTM A-36	38 890	$Z = 3.75 \times 10^{8}\sigma^{4.7}$ if $\sigma \leq 103$ $Z = 1.23 \times 10^{18}\theta^{0.0435\sigma}$ if $103 < \sigma \leq 310$	$\varepsilon_{cr} = 1.03 \times 10^{-6}\sigma^{1.75}$
ASTM A-421	30 560	$Z = 1.95 \times 10^{8}\sigma^{3}$ if $\sigma \leq 172$ $Z = 8.21 \times 10^{13}\theta^{0.0145\sigma}$ if $172 < \sigma \leq 690$	$\varepsilon_{cr} = 92.6 \times 10^{-6}\sigma^{0.87}$

no way of knowing how the thermal conductivity would vary during the course of a physicochemical process developing at a finite rate and varying microstructure.

The points plotted as open or solid circles in the figures to be shown represent information developed using a variable-state technique[24] characterized by relatively small temperature gradients during the measurements. The accuracy of the method is estimated to be about ±7 percent for stable, low-porosity materials. Because of the difficulties described earlier, the accuracy of this method in temperature intervals of physicochemical instability cannot be firmly stated, let alone determined.

Due to the nonreversible microstructural changes brought about by heating, the thermal conductivity of building materials (and perhaps most other materials) is usually different in the heating and cooling cycles. Open and solid circles are used in the figures to identify thermal conductivity values obtained by stepwise increasing and stepwise decreasing the temperature of the sample, respectively.

SOURCE OF INFORMATION

Information on the properties of building materials at elevated temperatures is scattered throughout the literature. There are a few publications, however, that are particularly suitable for use by firesafety specialists. One such publication is a source of information on the thermal properties of 31 building materials in Groups L/I and I.[13] Comprehensive sources of information, specifically on concrete and steel, are also available.[25,26] Two reports[27,28] give much information on concrete and steel; finally, information on the thermal conductivity of more than 50 rocks (potential concrete aggregates) is described by Birch and Clark.[29]

GROUP L MATERIALS

Steel

The steels used in the building industry are either hot-rolled or cold-drawn. The structural steels and concrete reinforcing bars belong in the first group. These are ferrite-pearlite steels with a randomly oriented grain structure whose strengths depend mainly on the carbon content. The wires used in prestressing steels are cold-drawn, and are high-strength pearlitic steels with an elongated grain structure oriented in the direction of the cold work.

Information on the mechanical properties of two typical steels, a structural steel (ASTM A-36) and a prestressing wire (ASTM A-421), is presented in Figures 1-26.4 through 1-26.6 and Table 1-26.1.[30] Figures 1-26.4 and 1-26.5 are

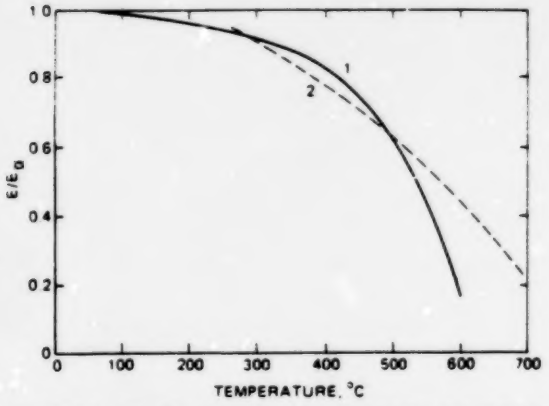


Fig. 1-26.7. The effect of temperature on the modulus of elasticity of (1) structural steels[31] and (2) reinforcing bars.[32]

stress-strain curves at room temperature and many elevated temperature levels. Figure 1-26.6 shows the effect of temperature on the yield and ultimate strengths for these two steels as evaluated from the stress-strain curves. Table 1-26.1 lists the material constants needed to describe the creep behavior of the two materials. Since creep is a very structure-sensitive property, the creep constants may differ significantly even for steels with similar characteristics at room temperature.

The modulus of elasticity is about 198 (± 3) × 10^3 MPa for a variety of common steels at room temperature. Figure 1-26.7 shows its variation with temperature for structural steels[31] and for steel reinforcing bars.[32] (E_0 in the figure is the modulus of elasticity at room temperature.)

Among the thermal properties of steel, thermal expansion is of interest in the design for firesafety. The thermal expansion is a structure-insensitive property. The dilatometric curve shown in Figure 1-26.8 is applicable to all common steels. Notable in the curve is a sudden decline at about 700°C, associated with the austenitic transformation of steel.

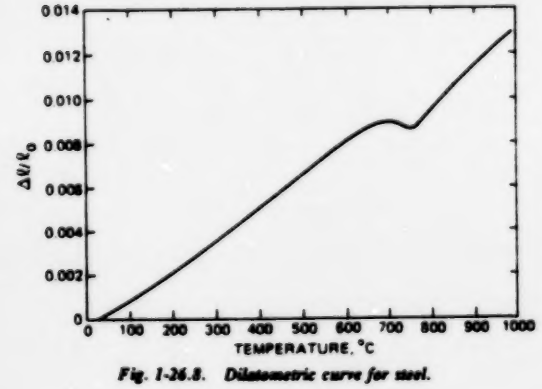


Fig. 1-26.8. Dilatometric curve for steel.

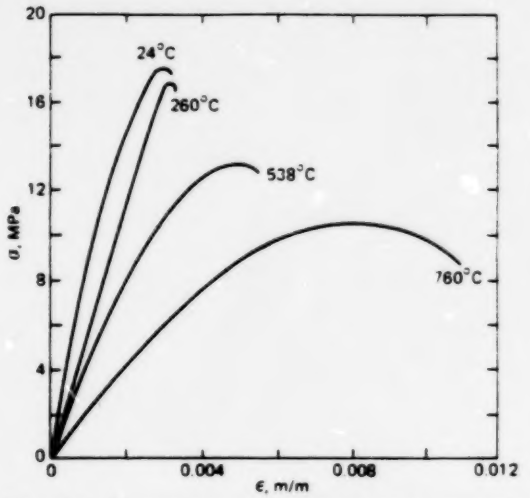


Fig. 1-26.9. Stress-strain curves for a lightweight masonry concrete at elevated temperatures.[33]

GROUP L/I MATERIALS

Concrete

The term concrete covers a large number of different materials, with the single common feature that they are formed by the hydration of portland cement. Since the hydrated cement paste amounts to only about 25 volume percent of the materials present, the properties of concrete may vary widely with the aggregates used.

Concretes are usually subdivided into two major groups: normal-weight concretes with densities usually in the 2200 to 2400 kg/m^3 range, and lightweight concretes with densities less than approximately 1850 kg/m^3. Firesafety specialists again subdivide the normal-weight concretes into

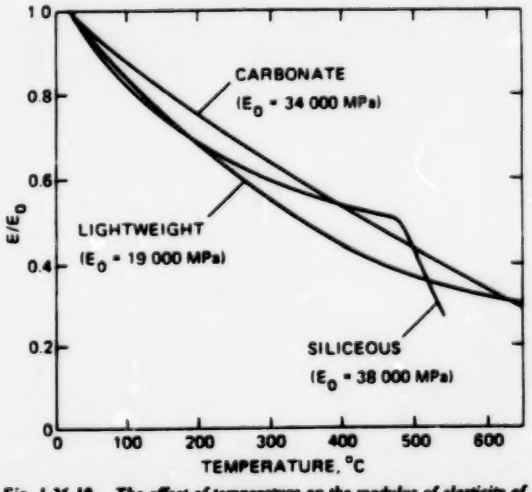


Fig. 1-26.10. The effect of temperature on the modulus of elasticity of concretes with various aggregates.[34]

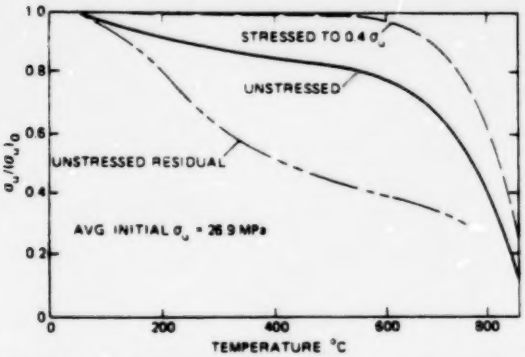


Fig. 1-26.11. The effect of temperature on the compressive strength of a normal-weight concrete with siliceous aggregate.[38]

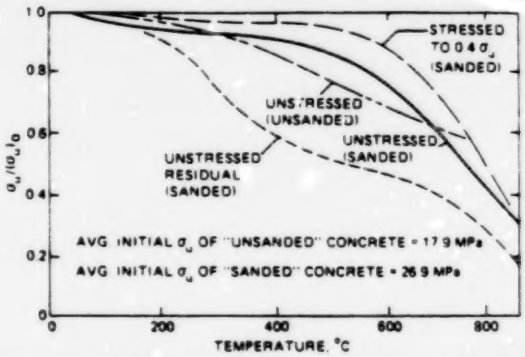

STRESSED TO 0.4 σ_u (SANDED)
UNSTRESSED (UNSANDED)
UNSTRESSED (SANDED)
UNSTRESSED RESIDUAL (SANDED)
AVG. INITIAL σ_u OF "UNSANDED" CONCRETE = 17.9 MPa
AVG. INITIAL σ_u OF "SANDED" CONCRETE = 26.9 MPa
$\sigma_u/(\sigma_u)_0$
TEMPERATURE, °C

Fig. 1-26.13. The effect of temperature on the compressive strength of two lightweight concretes.[38]

siliceous and carbonate aggregate concretes according to the composition of the principal aggregates used.

Among the mechanical properties of concrete, a considerable amount of information is available on the variation of modulus of elasticity and ultimate compressive strength of the material, while a limited amount of information is available on the complete stress-strain curves. Figure 1-26.9 shows the stress-strain curves for a lightweight concrete with expanded shale aggregate at room temperature and a few elevated temperature levels.[33] The shape of the curves may depend on the time of heating the test specimen at the target temperature level before the compression test.

Schneider[34] and Anderberg and Thelandersson[35] studied the stress-strain curves of normal-weight concrete at elevated temperatures under a number of loading conditions.

The modulus of elasticity may vary over a wide range, from 18 000 to 36 000 MPa, dependent mainly on the composition of the concrete. Using an optical method, Cruz[36] found that the decline of the modulus of elasticity with temperature does not depend significantly on the type of aggregate. (See Figure 1-26.10; E_0 in the figure is the modulus of elasticity at room temperature.) Other researchers[33,37] found little change up to about 200°C.

The ultimate strength of concrete may also vary over a wide range, and is influenced by such factors as age, nature and size of aggregate, amount of aggregate, and water to cement ratio. For normal-weight concretes the strength is usually between 20 and 60 MPa, and for lightweight concretes between 13 and 45 MPa.

The variation of ultimate compressive strength with temperature is shown in Figures 1-26.11 and 1-26.12 for normal-weight concretes with siliceous and carbonate aggregates, respectively, and in Figure 1-26.13 for two lightweight concretes.[38] [$(\sigma_u)_0$ in the figures is the ultimate strength at room temperature.] The specimens were heated to the target temperature either without load (curve "unstressed"), or with a superimposed load amounting to 40 percent of the ultimate strength (curve "stressed"). In a third series of tests the specimens were heated to the target temperature, then cooled to room temperature, stored at 75 percent relative humidity for six days, then tested (curve "un-

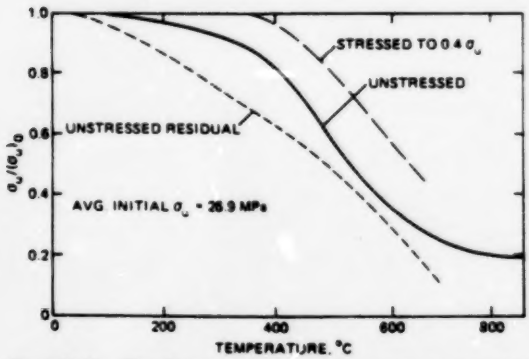


Fig. 1-26.12. The effect of temperature on the compressive strength of a normal-weight concrete with carbonate aggregate.[38]

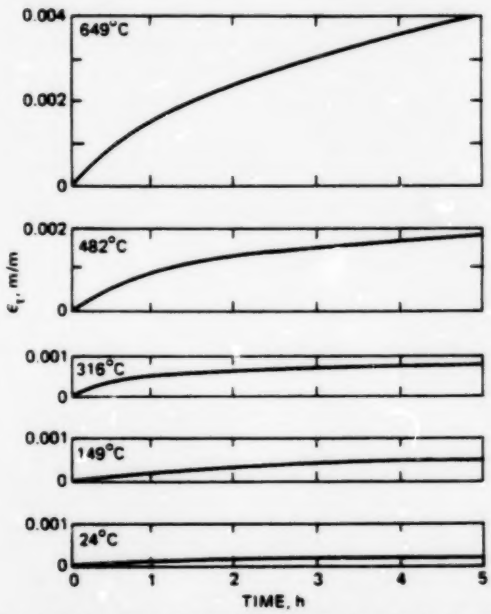


Fig. 1-26.14. Creep of a carbonate aggregate concrete at various temperature levels (applied stress: 12.4 MPa; compressive strength of the material at room temperature: 27.6 MPa).[43]

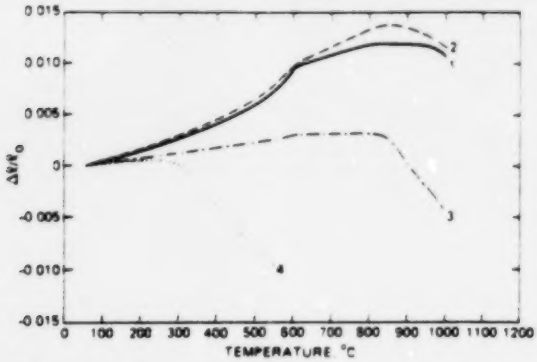


Fig. 1-26.15. Dilatometric curves for two normal-weight and two lightweight concretes.[17] (1) Normal-weight concrete with siliceous aggregate; (2) Normal-weight concrete with carbonate aggregate; (3) Lightweight concrete with expanded shale aggregate; and (4) Lightweight concrete with pumice aggregate.

stressed residual"). It was noted that the original strength of concrete between 27.6 and 44.8 MPa had little effect on the percentage decline of strength with the rise of temperature.

Further information on the strength of concrete at elevated temperatures is available.[33,37,39–42]

Some information on the creep of concrete at elevated temperatures is available from the work of Schneider[12] and Cruz.[43] The creep curves shown in Figure 1-26.14 are those recorded by Cruz for a normal-weight concrete with carbonate aggregates.

The dilatometric curves of two normal-weight concretes (with siliceous and carbonate aggregates) and two lightweight concretes (with expanded shale and pumice aggregates) are shown in Figure 1-26.15.[17] These curves were obtained in the course of a comprehensive study performed on 16 concretes. The type of aggregate apparently has a great influence on the shape of the curves.

The results of dilatometric and thermogravimetric tests were combined to calculate the density for these same concretes. The variation with temperature of the density of

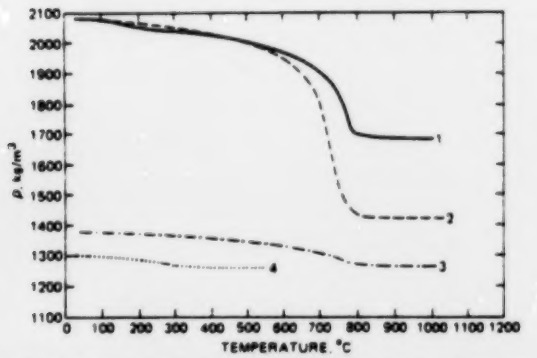


Fig. 1-26.16. Density of two normal-weight and two lightweight concretes.[17] (1) Normal-weight concrete with siliceous aggregate; (2) Normal-weight concrete with carbonate aggregate; (3) Lightweight concrete with expanded shale aggregate; and (4) Lightweight concrete with pumice aggregate.

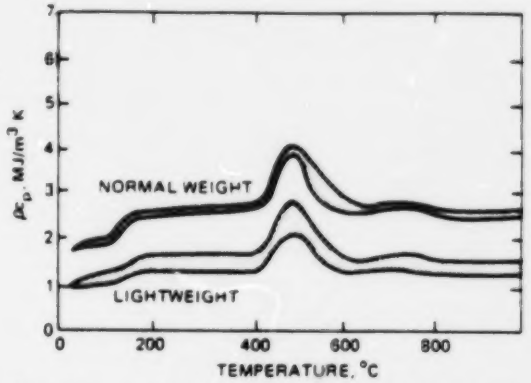


Fig. 1-26.17. Usual ranges for the volumetric specific heats of normal-weight and lightweight concretes.[5]

the four concretes in Figure 1-26.15 is shown in Figure 1-26.16. The partial decomposition of aggregate is responsible for a substantial drop (above 700°C) in the density of concretes made with carbonate aggregates.

The apparent specific heat of various concretes was studied both theoretically[5] and experimentally.[13] The usual range of variation of the volumetric specific heat (i.e., the product ρc_p) for normal-weight and lightweight concretes is shown in Figure 1-26.17. This information, derived by combining thermodynamic data with thermogravimetric observations, has since been confirmed by differential scanning calorimetry. Experimental data on a few concretes and some of their constituents is available.[13]

Since approximately 75 percent of a concrete consists of aggregates, it is not surprising that the thermal conductivity of a concrete depends mainly on the nature of its aggregates. In general, concretes made with dense crystalline aggregates show higher conductivities than those made with amorphous or porous aggregates. Among common aggregates quartz has the highest conductivity, and therefore concretes made with siliceous aggregates are on average more conductive than those made with carbonate aggregates.

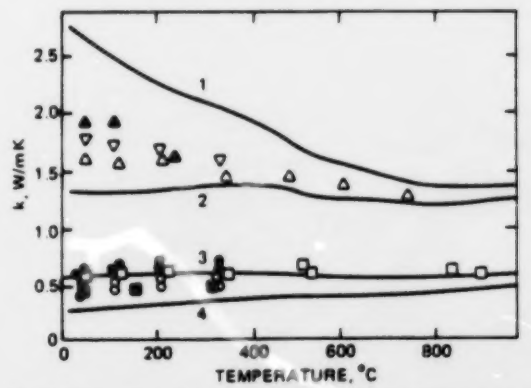


Fig. 1-26.18. Thermal conductivity of four "limiting" concretes and some experimental thermal conductivity data.[5] Triangles represent various gravel concretes; solid circles are expanded slag concretes; squares are expanded shale concretes; and open circles are pumice concretes.

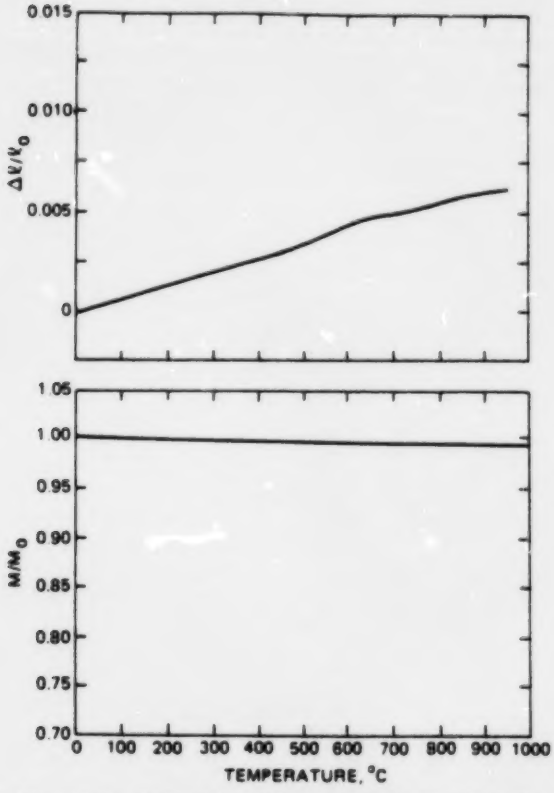


Fig. 1-26.19. Dilatometric and thermogravimetric curves for a clay brick.[13]

Derived from theoretical considerations,[5] the four solid curves in Figure 1-26.18 represent the variation of the thermal conductivity of four concretes. Two concretes (Nos. 1 and 2) represent limiting cases among normal-weight concretes, and the other two concretes (Nos. 3 and 4) among lightweight concretes. Figure 1-26.18 also contains some

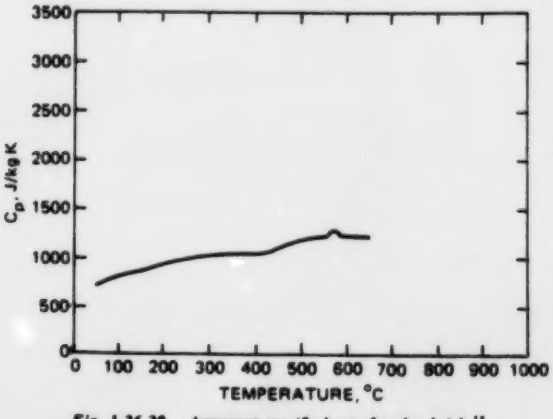


Fig. 1-26.20. Apparent specific heat of a clay brick.[13]

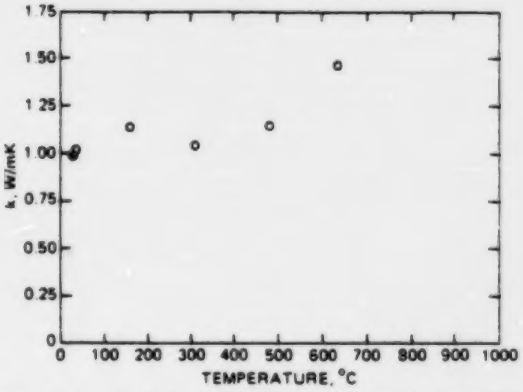


Fig. 1-26.21. Thermal conductivity of a clay brick.[13] *Open circles denote points in the heating cycle; solid circle is after cooling.*

experimental data that indicate that the upper limiting case is probably never reached with aggregates in common use, and that the thermal conductivity of lightweight concretes may be somewhat higher than predicted using theoretical considerations.

Further experimental information on the thermal conductivity of some normal weight[13,17] and many lightweight concretes[17] is available.

Brick

The density of bricks range from 1600 to 2500 kg/m^3, depending on the raw materials and the firing process, which together determine the porosity of the brick. Their strength may also vary over a wide range, from 10 to 110 MPa, dependent again on these two factors. Since, owing to the presence of mortar joints, brick walls rarely display a strength much over 15 MPa, they are usually not considered for important load-bearing roles in buildings. Consequently, there has been little interest in the mechanical properties of bricks at elevated temperatures.

The dilatometric and thermogravimetric curves for a clay brick of 2180 kg/m^3 density are shown in Figure 1-26.19. The variation of its specific heat and thermal conductivity

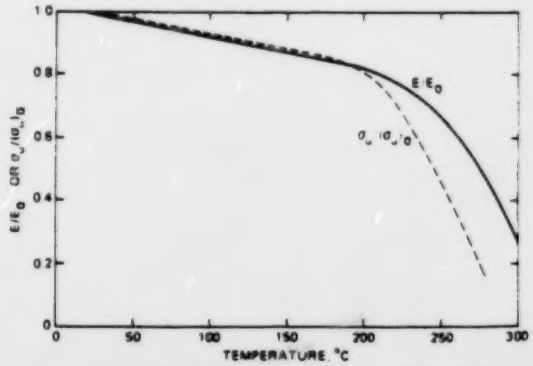


Fig. 1-26.22. The effect of temperature on the modulus of elasticity and compressive strength of wood.[66–68]

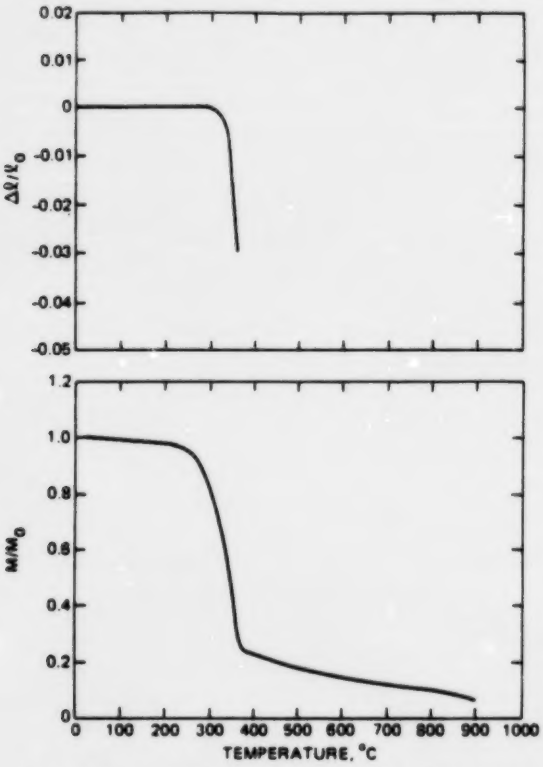


Fig. 1-26.23. Dilatometric and thermogravimetric curves of pine.[13]

with temperature is shown in Figures 1-26.20 and 1-26.21, respectively.[13]

Wood

The density of soft woods used in the construction industry ranges from 300 to 490 kg/m^3 in oven-dry condition. Their modulus of elasticity is usually between 6.5 × 10^3 and 11.0 × 10^3 MPa, and their strength in compression (parallel to grain) between 20 and 45 MPa. Figure 1-26.22 shows the variation of the modulus of elasticity and compressive strength of oven-dry, clear wood with temperature.[44-46] [E_0 and $(\sigma_u)_0$ in the figure are modulus of elasticity at room temperature and compressive strength at room temperature, respectively.]

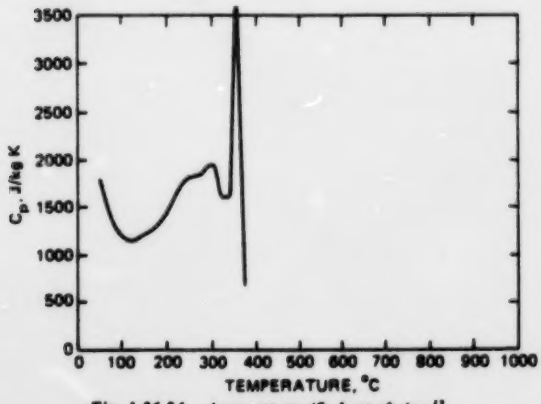


Fig. 1-26.24. Apparent specific heat of pine.[13]

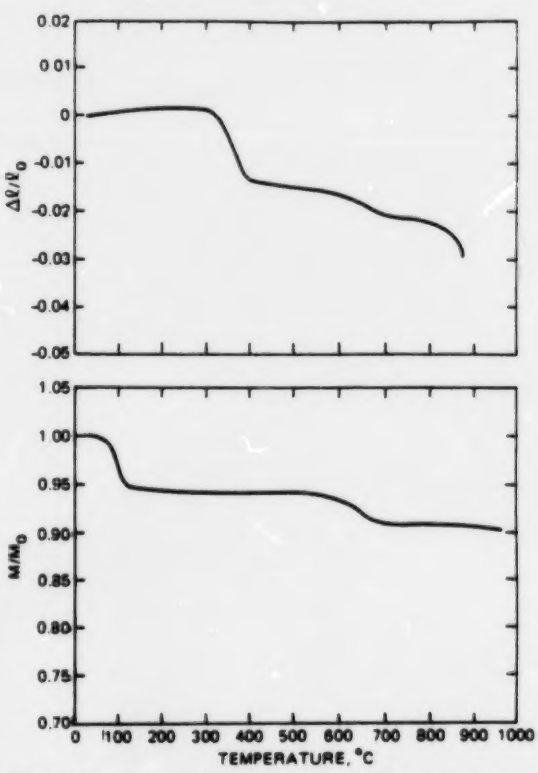


Fig. 1-26.25. Dilatometric and thermogravimetric curves for a gypsum board.[13]

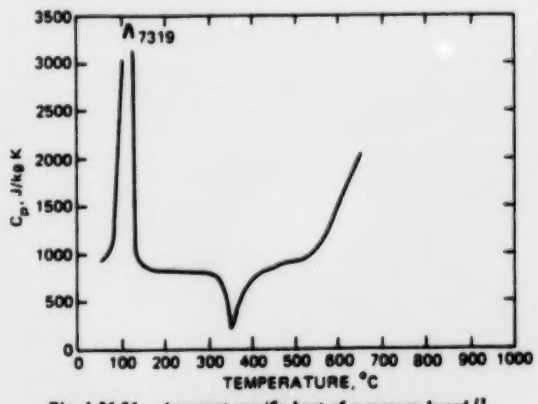


Fig. 1-26.26. Apparent specific heat of a gypsum board.[13]

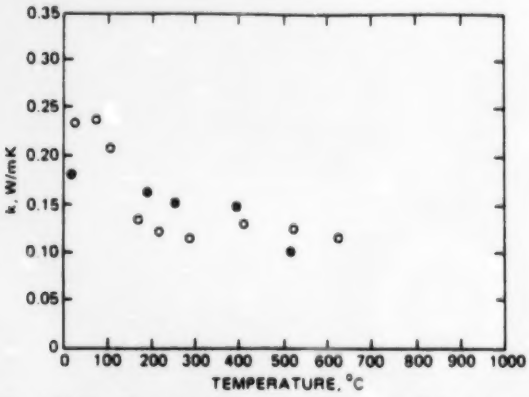


Fig. 1-26.27. Thermal conductivity of a gypsum board.[13] Open circles are points in the heating cycle; solid circles are points in the cooling cycle.

The thermal conductivity of a pine with 400 kg/m^3 density was measured as 0.86 to 0.107 W/m K between room temperature and 140°C.[13] Its dilatometric and thermogravimetric curves are shown in Figure 1-26.23, and the variation of its apparent specific heat with temperature is shown in Figure 1-26.24.

GROUP I MATERIALS

Gypsum.

Gypsum ($CaSO_4 \cdot 2H_2O$) is an ideal fire protection material. On heating, it will lose the two H_2O molecules at temperatures between 100 and 160°C, depending on the rate of heating. The heat absorbed in the decomposition of gypsum retards the penetration of heat into the protected structure.

The variation of the volumetric specific heat of pure gypsum with temperature is shown in reference 47, based on information reported in the literature.[48,49] The dilatometric and thermogravimetric curves of a fire-resistant gypsum board of 678 kg/m^3 density are shown in Figure 1-26.25. The apparent specific heat versus temperature curve for the same gypsum board is shown in Figure 1-26.26. Figure 1-26.27 gives some information on its thermal conductivity on heating and cooling.

Miscellaneous Other Materials

Information is available on the dilatometric and thermogravimetric behavior, apparent specific heat, and thermal conductivity of a number of materials in Group I, including: asbestos cement board, expanded plastic insulating boards, mineral fiber fireproofing, arborite, and glass-reinforced cement board.[13]

NOMENCLATURE

- c specific heat, J/kg K
- $\bar{c}$ specific heat for a mixture of reactants and solid products, J/kg K
- d_p characteristic pore size, m
- E modulus of elasticity, MPa
- F material constant, dimensionless
- h enthalpy, J/kg
- ΔH activation energy for creep, J/kmol
- ΔH_p latent heat (at constant pressure) associated with a conversion, J/kg
- k thermal conductivity, W/m K
- ℓ dimension, m
- $\Delta\ell = \ell - \ell_0$
- M mass, kg
- n material constant, dimensionless
- P porosity, m^3/m^3
- R gas constant, J/(kmol)K
- S specific surface, m^2/m^3
- t time, h
- T temperature, K (or °C)
- v volume fraction, m^3/m^3
- w mass fraction, kg/kg
- Z Zener-Hollomon parameter, h^{-1}

Greek letters

- α expression defined by Equation 3, dimensionless
- ε strain (deformation), m/m
- ε_{f0} creep parameter, m/m
- $\dot{\varepsilon}_{ss}$ rate of secondary creep, h^{-1}
- θ temperature-compensated time, h
- ζ reaction progress variable, dimensionless
- π material property (any)
- ρ density, kg/m^3
- σ stress, MPa
- σ Stefan-Boltzmann constant, W/m^{2}K^4

Subscripts

- i of the ith constituent
- o original value at reference temperature
- s of the solid matrix
- p at constant pressure
- R due to radiation
- t true
- t time dependent
- T at temperature T
- u ultimate
- y yield

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